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OPTIMIZATION OF PLANTING AREA FOR BROCCOLI, CABBAGE AND SQUASH IN THREE FARMS, CARTAGO, COSTA RICA

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Abstract:

The annual per capita consumption of vegetables in Costa Rica increased 14 kilograms from 2002 to 2015, because of the adoption of low-calorie diets with high vitamin and nutritional intake. To supply the requirements of the population, it is necessary to develop models that optimize the use of productive resources. For this reason, the objective of this research is to develop a model to optimize the production area of broccoli, cabbage, and squash in three farms in Cartago, Costa Rica. Data were collected in the field during 2021 and the optimization model was solved by linear programming to maximize the profitability of each farm. The results showed that it is possible to make an efficient use of the available land maximizing the farmers' profit, although water and area limitations prevent covering all the market demand. It is concluded that farmers improve their business decisions based on models that optimize limited resources.

Keywords: *Agricultural economics, agricultural markets, linear programming, profitability, food supply.*
JEL Codes: *C61, M21, Q12.*

1. Introduction

The last National Agricultural Census of Costa Rica registered 4,698 farms dedicated to the production of vegetables, 53% were in the province of Cartago due to the favorable climatic and soil conditions of the region (INEC, 2014). Of these, 336 farms with broccoli (Brassica oleracea var. Italica) and 750 with cabbage (Brassica oleracea var. Capitata) were reported (INEC, 2014), however, due to the size of the farms (between 1 and 5 hectares) and markets, none of these productive units is dedicated exclusively to a single crop.

Specifically, there are broccoli production data for 229.5 hectares (INEC, 2014). In the case of cabbages, from 1998 to 2022 an average of 750 hectares per year was planted, however, in the last three periods the average decreased to 565 hectares, equivalent to 18,830 tons of harvested product (FAO, 2023).

In turn, the per capita consumption of cabbage and broccoli in Costa Rica was 12.96 kg and 3.09 kg in 2015, respectively (PIMA, 2016), however for pumpkin (Cucurbita pepo L.), it is not it reports information separately and is included in a category of "other vegetables". This consumption is reflected in the cost/income ratio of Costa Rican households in such a way that for broccoli it is 0.026%, for cabbage it is 0.068% and for pumpkin it is 0.015%, the above, according to the percentage of average expenditure by income deciles. in the population (INEC, 2019).

Because in recent years, these production systems have been affected by the effects of climate change, the pressure of pests and diseases, the general increase in costs, and urban growth (Campaña, 2011; Ramírez-Vargas & Nienhuis, 2012), the need to optimize production costs is analyzed with the intention of maximizing the profits of small farmers who do not have advanced technologies for their farms. For this, linear programming is an efficient technique to distribute limited resources and provides information that can be used in crop planning, land use and production inputs in a way that guarantees the sustainability of agribusiness (Alvarado-Boirivant, 2009; Diaz, 2005).

The objective of this research is to develop a model that optimizes the profitability of the annual production of three vegetables (broccoli, green cabbage, and pumpkin) in three different farms in Cartago, Costa Rica and that, in addition, is an input for the strategic analysis of the farmers when deciding the crop area to plant according to their conditions and resources.

2. Literature Review

Linear optimization is used to solve decision problems in which the objective is expressed as a linear function with two or more variables and the requirements that must be satisfied are expressed through linear equations and inequalities (Jornet Plá et al., 2004). The allocation of resources through linear programming is one of the most common ways to achieve an optimization objective, be it the maximization or minimization of a function that responds to a problem. In this sense, there are different researchers who have used linear programming as a tool to maximize profits or minimize costs in agribusiness.

Boirivant (2009) worked with crops such as onion, carrot, cabbage, potato, corn for corn and sweet pepper, to maximize profits through the optimal combination of the production of each crop, obtaining four scenarios based on price. dual. He also used a linear programming model for optimization in an agricultural settlement in La Cruz de Guanacaste, Costa Rica, to maximize profits and find the optimal value of production (Boirivant, 2013).

In Ecuador, an optimization model was designed for potato cultivation that determined the amount of nutrients necessary to achieve a yield of 50 t/ha, based on seven commercial fertilizer formulations of thirty different alternatives, avoiding excesses or deficits of nutrients in cultivation (Campaign, 2011). Despite the good results obtained, his research did not consider the economic effect on the profitability of the crop when reaching the desired yield, as is the case of (Villavicencio, 2014), who proposed a linear programming model to maximize the gross margin of profit with the diversification of seven crop alternatives in an agricultural property in Chile. The first results of Villavicencio (2014), indicate that only 39% of the available area should be used in two different crops (tomato and melon), restricted by the demand for water, production inputs and capital, while the 50% increase in capital led to a 44% increase in gross margin through the diversification of five different crops and with ease in the other restrictions (Villavicencio, 2014).

For its part, in Honduras, the case of an agribusiness with different production activities of annual and perennial crops, livestock, and sale of minor agricultural services was studied (García, 1999). Despite maintaining a diversified crop structure, the agroindustry's ability to adapt and compete was slow, as there were no changes in production activities. For this reason, (García, 1999) designed a series of linear programming models combining traditional and new activities, and even though six out of eight models suggested expanding the line of products and services to maximize profitability at different levels, it was recommended continue with traditional activities when capital was reduced.

A similar study was carried out in Argentina with a tobacco and other minor crop agribusiness, which maintained a positive gross profit margin in the financial structure, but cash flows were negative and limited its operation (Montenegro, 2021). In order to improve the productive structure and financial indicators, a linear programming model was applied to replace a 10 ha lot of tobacco with the incorporation of new crops, but the results suggested using only 7 ha in peach and vine, enough to generate a 68% increase in gross margin and 108% in cash flow (Montenegro, 2021).

Linear programming has also been useful to define crop rotation and soil rotation plans, as is the case of Kharisma & Perdana (2019), who developed a weekly programming plan for one year that would maximize economic benefits, minimize excess production, and optimize the rotation of the baby Kenyabean crop with three different combinations of tomato, carrot and potato crops.

In a case study of an open field mixed vegetable family farm in Slavonija, Croatia, linear programming was applied to maximize profit and optimally allocate agricultural land (Grubišić et al., 2019). The farm allocated 4.1 ha to the production of vegetables, with the main limitation of labor that forced them to keep only tomato, peppers, cucumber, and potato in the system (Grubišić et al., 2019). Despite the conditions, with crop rotation, the net yield of the farm increased 43% and almost all the areas determined for each product reached the maximum limit allowed, which indicates that expansion should be considered if there is greater availability of land. and the possibility of selling all the production.

The common denominator of the restrictions on agricultural crops is the availability of productive inputs and capital (Montenegro, 2021; García, 1999; Villavicencio, 2014; Boirivant, 2013; Campaña, 2011; Boirivant, 2009). But these can be more specific and technical, for example, restricting the capacity of conducting water and pumping in an irrigation district, as is the case of Ortega-Gaucin et al. (2009), who maximized the net income of an agricultural district in Chihuahua, Mexico, with fifteen crop alternatives to mitigate the negative effects of drought and an oversupply of similar products in the market.

Another of the restrictions of Ortega-Gaucin et al. (2009) was to limit the maximum area in the most profitable crops and with the highest water demand to avoid bias in the results by prioritizing these crops over others and impairing diversification, in addition to restricting the minimum area of some current perennial crops to ensure their production.

Finally, this method has also been used to plan the farms in a settlement and maximize the number of people to feed according to the annual nutritional requirements in energy, animal protein, vegetable protein and vegetables (Roche et al., 2003), although the results were limited with respect to the number of productive activities considered.

3. Method

3.1 Data

The information was collected during the 2021 period for the farms located in the upper area of Cartago, Costa Rica, with temperatures ranging between 18° and 24°C, which share general technical cultivation specifications but present different management environments. of water for irrigation and from this information, the average production cost structures of the three crops on each farm were generated. Subsequently, three farms were selected that present conditions for the planting of the three crops and that have 4, 6 and 5 hectares of land respectively. These farms are owned by the same family group that collaborates in the same sales market, which has demand limits according to their inventory turnover statistics.

The average prices paid on the farm were used, obtained from the weekly information published by the National Production Council (CNP) from January 2021 to April 2022, which were corroborated in the interviews with the producers. The prices per kilogram used were US$1.1964, US$0.4539, and US$0.5146 for broccoli, cabbage and pumpkin, respectively, which may change according to market conditions.

Table 1 presents the information on the average production costs per hectare and per farm for each crop, as well as the average productivity obtained by the producer and the corresponding profits. It should be noted that both costs and yields correspond to the time of information collection and may change according to existing climatic conditions, mainly in terms of the use of agrochemicals to treat pests and diseases. Also, the growing cycle can span from 70 to 90 days for broccoli, 100 to 140 days for cabbage, and 90 to 120 days for squash.

Table 1. Production costs, yields and profits per hectare and crop for each farm, 2021

Farm	**Crop**	**Variable**	**Yield (ton/ha)**	**Costs (US$)[1]**	**Profit (US$)[1]**
1	Broccoli	B_{11}	12.70	5 741.82	9 452.70
1	Cabbage	C_{11}	30.00	4 776.19	8 843.73
1	Squash	P_{11}	15.70	2 743.58	5 336.59
2	Broccoli	B_{12}	15.45	5 167.64	13 317.03
2	Cabbage	C_{12}	40.00	5 969.58	12 190.31
2	Squash	P_{12}	15.00	3 292.30	4 427.61
3	Broccoli	B_{13}	14.10	5 397.31	11 472.19
3	Cabbage	C_{13}	34.00	5 909.88	9 526.02
3	Squash	P_{13}	14.20	3 193.53	4 114.65

Note: 1/ Original data was collected in colones (Costa Rica's official currency) and expressed in U.S. dollars, with an exchange rate of 670.36 colones per dollar, April 2022.

3.2 Objective function and linear constraints for mathematical model

Linear programming is about maximizing or minimizing a linear function of several primary variables, called the objective function, subject to a set of linear equalities or inequalities called constraints, with the additional condition that none of the variables can be negative (Weber, 1984; Boirivant, 2009; Gonzáles, Sabando & Barcia, 2018; Beneke & Winterboer, 1984). This study uses the following mathematical model to maximize the utility of the three crops on the three farms:

$$F(U) = xB_{11} + xC_{11} + xP_{11} + xB_{12} + xC_{12} + xP_{12} + xB_{13} + xC_{13} + xP_{13} \quad (1)$$

Where,
x = profit per hectare per productive cycle;
B_{11} = hectares planted with broccoli on farm 1;
C_{11} = hectares planted with cabbage on farm 1;
P_{11} = hectares planted with pumpkin on farm 1;
B_{12} = hectares planted with broccoli on farm 2;
C_{12} = hectares planted with cabbage on farm 2;
P_{12} = hectares planted with squash on farm 2;
B_{13} = hectares planted with broccoli on farm 3;

C_{13} = hectares planted with cabbage on farm 3;
P_{13} = hectares planted with squash on farm 3.

Gross profit for each crop and farm was estimated as the difference between total income and production costs as follows (Eq. 2):

$$U_{ij} = (P_{ij} * x_{ij}) - Cp_{ij} \quad (2)$$

where U_{ij} is the gross profit per hectare for crop *j* in farm *i*; P_{ij} is the sales price per ton for crop *j* in farm *i*; x_{ij} is the yield in tons harvested for crop *j* in farm *i*; Cp_{ij} are the variable and fixed production costs per hectare for crop *j* in farm *i*.

The linear constraints that limit utility maximization are described in Table 2 together with their mathematical expression.

Table 2. Linear constraints for optimization model

Constraints	Description	Equation[1]
Harvest area (HA)	Each farm has a cultivable area of 4, 6 and 5 hectares, respectively. For the equivalent of one harvest, the market requires between 60 and 300 tons of broccoli, between 50 and 450 tons of cabbage, and between 100 and 215 tons of squash. In addition, growers are willing to plant one or all three crops at the same time.	$HA_{ij} \leq 4\,; 6\,;\ 5$
Farm labor (FL)	The labor required is measured in 6-hour days and the hours indicated by the producers during the last period were used. Labor hours for manual planting, weed control, agrochemical application, harvesting and other minor tasks were included.	$FL_{ij1} + \cdots + FL_{ijn} \leq 450\,; 650\,;\ 540$
Irrigation water (IW)	Each farm uses different irrigation systems and has available water of 9.0, 18.0 and 9.5 m3, respectively. Depending on the climatic and edaphic conditions in the study area, the irrigation requirement varies, so it was standardized for each of the crops.	$IW_{ij1} + \cdots + IW_{ijn} \leq 9\,; 18\,;\ 9.5$
Use of machinery (UM)	Land preparation is done with hired machinery and may include plowing, harrowing, furrow and row preparation. The model considers the hours used by farmers in the last production cycle, since each farm requires different preparation times. There are no limitations in the use of machinery and there is sufficient availability of the service.	$UM_{ij1} + \cdots + UM_{ijn} \geq 0$
Budget (BG)	Farmers have the necessary financing for the crop cycle through the Development Banking System and microfinance institutions that support the agricultural sector. The model does not include a capital constraint; however, the budget requirement is calculated once the other variables are optimized.	$BG_{ij} \geq 0$

Note: 1/ Crop *i* in farm *j* for the work from *1* to *n*.

3.3 Solution method

Regarding the use of software for the solution of the proposed linear programming model, it is common to use the Microsoft Excel® SOLVER add-on using electronic spreadsheets, which uses the simplex method developed by George Dantzig in 1947, for solving multiple application problems (Grubišić et al., 2019; Montenegro, 2021; Ortega-Gaucin et al., 2009; Villavicencio, 2014). There is also specialized software that were not used in this research, such as TORA Optimization System, OR Brainware Decision Tools, and LINGO, which allows working on linear programming at advanced levels, as is the case of Campaña (2011), Navarro (2011) and Conejero (2013), respectively.

4. Results and Discussion

The results presented in this research article are limited to information from three different producers in Cartago, Costa Rica, who have different areas for vegetable production and differences in yields, costs, and profits, as well as different technologies and production conditions that affect profitability.

Table 3 shows the profit before optimization comparing farms 2 and 3 with farm 1 as a reference in the scenario that all farmers can plant one hectare of each crop, the profit of farm 1 would be US$23,633 while farms 2 and 3 present profits of US$29,934.95 (26.67% higher than farm 1) and US$25,112.86 (6.26% higher than farm 1) respectively. Note that the greatest utility of the broccoli and cabbage crops are found on farm 2, while the squash crop presents on farm 1. These results coincide with the behavior of the yield in ton/ha, which the higher it is, generates more utility.

Table 3. Indicators compared to farm 1 under the assumption of harvesting one hectare for each crop

Farm	Variable	Yield		Cost		Profit	
		Ton/ha	Variation	US$/ha	Variation	US$/ha	Variation
1	B_{11}	12.70	-	5 741.82	-	9 452.70	-
1	C_{11}	30.00	-	4 776.19	-	8 843.73	-
1	P_{11}	15.70	-	2 743.58	-	5 336.59	-
Total						*23 633.02*	-
2	B_{12}	15.45	21.65%	5 167.64	-10.00%	13 317.03	40.88%
2	C_{12}	40.00	33.33%	5 969.58	24.99%	12 190.31	37.84%
2	P_{12}	15.00	-4.46%	3 292.30	20.00%	4 427.61	-17.03%
Total						*29 934.95*	*26.67%*
3	B_{13}	14.10	11.02%	5 397.31	6.00%	11 472.19	21.36%
3	C_{13}	34.00	13.33%	5 909.88	23.74%	9 526.02	7.71%
3	P_{13}	14.20	-9.55%	3 193.53	16.40%	4 114.65	-22.90%
Total						*25 112.86*	*6.26%*

With these indicators, it is expected that the linear programming model prioritizes the production of broccoli and cabbage on farms 2 and 3, and the production of pumpkin on farm 1, although these results are subject to the interaction of the three farms in the client market and the specific restrictions of each one.

Table 4 shows the results of the optimization model, presenting a total use of the area available for planting on farms 1 and 2, while farm 3 uses 91.60% of the available land because it is limited by water. for irrigation. The model indicates which crops should be planted on each farm in a divided way, to cover the supply necessary to serve the market they share and maintain the independence of each producer at the operational level.

Table 4. Area optimization results in three model farms.

Farm	Brocco li	Cabbage	Squash	Available area	Optimized area
1	0.00	0.81	3.19	4.00	4.00
2	5.36	0.64	0.00	6.00	6.00
3	1.06	0.00	3.52	5.00	4.58
Total area	***6.42***	***1.45***	***6.71***		

According to the suggested optimized area for the crops, the calculated production costs and the historical yields, the gross profit results of the model show that farm 2 is the most profitable per arable hectare and its profit depends especially on broccoli production. In the case of farm 1, only two of the products are planted, the above, because it presents high costs in Broccoli compared to the other two farms, however, this cost is close to that obtained by SEPSA (2021). On farm 2, the discrimination of the squash crop is mainly due to the availability of water for irrigation and the preference towards the broccoli crop in terms of profitability.

All the farms obtain higher profits in this optimized model, than before doing so, as observed in table 5.

Table 5. Results of profit optimization in USD for the three farms of the model

Finca	Broccoli	Cabbage	Squash	Gross Profit
Finca 1	0	7 188	17 009	24 197
Finca 2	71 374	7 806	0	79 181
Finca 3	12 184	0	14 477	26 661

Due to the size of the farms and the availability of water, the production obtained covers 32.6%, 11.1% and 46.5% of the maximum demand of the local market to which they attend. Farms 1 and 3 make full use of the available water, while farm 2 uses 95%, that is, it maintains a clearance of 0.9 m3 of water.

According to the proposed sowing scheme, the available wages are used as follows: 80.6%, 95.7% and 70.2% respectively on each farm. In addition, machinery is used for 19, 78 and 17 hours to prepare the land. Regarding the budget, farm 1 requires US$12,626, farm 2 requires US$31,519 and farm 3 needs US$16,968.

This linear programming model shows that there is efficiency in crop rotation on a scheduled basis, as explained by Kharisma & Perdana (2019), Boirivant (2009, 2013) and Villavicencio (2014) in their research. In all cases, the need to have sufficient resources for irrigation, capital and production inputs is evident, as the main limitations of optimization in agricultural processes. In the same way, crop diversification is promoted at different times of the year, just as (Ortega-Gaucin et al., 2009) did to manage the risk of drought.

Despite the fact that the proposed model does not restrict the use of capital like García (1999), Montenegro (2021), Villavicencio (2014), and it is based on the assumption that the farmer has access to it, it is necessary to know the specific cost of each producer to determine the needs of financial resources that must be used and that are part of the economic viability of the activity.

5. Conclusions

Based on the suggested optimization model, the area to be cultivated with broccoli, cabbage and squash on each farm was estimated to maximize profitability and avoid saturation of the same product in the client market due to lack of planning. In addition, the profit obtained with this optimization method improves to be higher than what the producer normally obtains with monoculture.

The area optimized for broccoli crop was allocated primarily to farm 2 because, due to the producer's management conditions and the availability of resources, it is the farm that generates the highest profit per hectare. Contrary to the allocation of land to the cabbage crop, which was given in a smaller proportion because it has the highest average costs compared to the other crops.

Since producers work individually, but serve the same client market, the results of the proposed model could change to the extent that producers wish to mitigate market risk and always keep the three crops in production on each farm, or that the client market demands a greater quantity of a specific product. Therefore, the profit would be maximized in a different amount, but there would always be a limitation in the production resources and the capital necessary to finance the agricultural activities.

The results of this research show it is possible to organize producers in the same area, who grow the same crops and serve the same market, in such a way as to promote competitiveness, productive linkages and improve individual profits. These conditions could improve the permanence of rural agribusinesses over time.

It is worth clarifying that, given that Costa Rica has a great variety of climates, topographies and soils, this model should not be generalized, but it is advisable to apply it with the pertinent adjustments to different zones, conditions, and producers in order to improve decision making.

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